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ACTIVE COMBUSTION CONTROL FOR MILITARY GAS TURBINE ENGINES

Marcus H. Richman and Michael S. Richman
Naval Air Systems Command
Propulsion and Power Engineering
22195 Elmer Road, Unit 4
Patuxent River, MD 20670-1534
USA

INTRODUCTION

The U.S. Navy, as a participant in the United States' Integrated High Performance Turbine Engine Technology (IHPTET) initiative, is dedicated to increasing aircraft engine performance to satisfy the propulsion requirements of future Navy aircraft. This is accomplished by identifying the propulsion requirements, in terms of performance and total cost, for specific Navy aircraft. The required engine technology advances are then broken down into specific engine component technology objectives. Advanced technology is then developed on the component level. Once an appropriate level of readiness is reached, the components are then assembled into an engine for overall advanced propulsion system demonstration. Technologies from this demonstrator engine are then made available to development engine programs, such as the Joint Strike Fighter (JSF), for further development and eventual transition to production engine programs.

The figure of merit used to measure performance is engine thrust/weight ratio. The role of the combustor in this endeavor is to provide the necessary temperature rise to increase core engine output. This drives the combustor to operate at higher fuel/air ratios which in turn drives a larger portion of the combustor volume to operate at or near stoichiometric conditions. Combustor operation at these levels must be achieved with an eye to numerous other parameters such as durability, weight, cost and emissions. Active Combustion Control is one of the key technologies required to meet these objectives simultaneously.

CONTROL SYSTEMS DESIGN

Propulsion controls technology programs have a two-fold focus. They funnel technologies into both legacy systems as well as the F414 and JSF programs (short term), and develop fundamental capabilities for future (2003 and beyond) propulsion systems. These programs revolve around two primary requirements; increased thrust-to-weight and reduced life cycle cost (LCC). Both have multiple primary technology development paths, which contain revolutionary control system (diagnostic and prognostic) components as enabling technology requirements.

Increasing thrust-to-weight can be accomplished in two primary ways. First, use exotic materials to reduce the weight of individual components: compression systems, fan, turbine, combustor/augmentor, controls and accessories (i.e. pumps, actuators, sensors, and electronics). Second, the system design must be weight optimized. The major components must lose weight via envelope reduction. Reduce core weight by reducing the number of stages required for fans, compressors, and turbines. Reduce length of combustor and augmentor. Putting the core on a diet, via the above methods, results in a much lighter system (good), but an extremely unstable (bad) one. As a result, the engine must be smarter. The major components must be actively controlled, avoiding stall, surge, and vibration (HCF) in the rotating components, as well as closed loop combustion to ensure efficient burning, and emission development within a shortened envelope. Cooperative with the use of exotic materials for the hot section, active

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combustion control is the answer for improved performance, durability, and safety. Figure 1 illustrates this degradation of the hot section components (turbine inlet) as we push the limits of combustion performance.

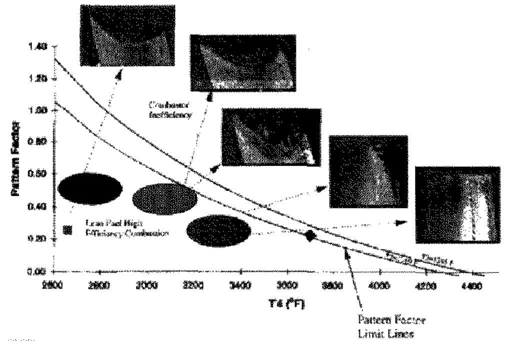

Figure 1

The technology involved in control system design for active combustion control relies primarily on actuation and sensing. The algorithms will be heavily laden with information fusion technology, combining a meriod of sensor inputs not only from the combustion system, but the entire engine. The true advantage of active combustion control will be as a component in a larger adaptive engine control algorithm providing the capability to optimize on performance, life, damage tolerance, and economy. Both systems will blur the lines between controls and diagnostics. Both systems will be model based, providing the necessary baseline and backup for each of the sensor suites. Active combustion control will not be based on a "point" type feedback which relies on "safe" operating limits around singular sensor information. Temperature, pressure, vibration levels, etc.. will all feed together providing a combustion system level feedback for use in actuating the combustion, aero, acoustic, and nox dynamics.

HIGH FUEL/AIR OPERATION

The most effective way of increasing engine output is to increase the energy added by the combustion of the fuel. In practice this means increasing the average combustor exit temperature (T4) by increasing the fuel air ratio (FAR). Traditionally, turbine materials and cooling technology have limited the exit temperature. As advances have been made in these areas, T4 has increased to take advantage of the increased capability [Figure 2]

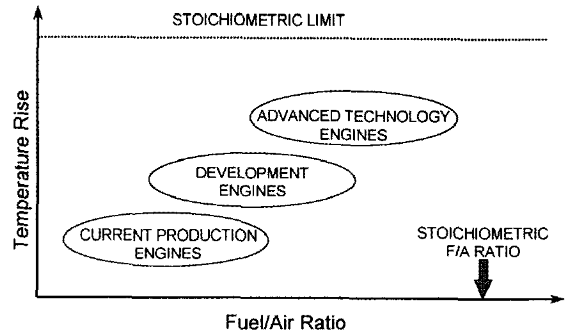

Figure 2

Combustor behavior is fairly well characterized at fuel/air ratios below 0.04. At these lower fuel/air ratios, the incidences of locally stoichiometric streaks exiting the combustor are infrequent. As the average FAR increases above 0.04, these locally stoichiometric streaks become more prevalent. As these stoichiometric steaks leave the combustor, and enter the turbine, they react with cooling air introduced in the turbine. This reaction produces enough energy to quickly destroy turbine hardware. Active Combustion Control offers a technology that may be able to address this problem.

COMBUSTOR EXIT FLOW CONTROL

Combustor exit temperature is usually quoted as an average temperature that is appropriate for performance calculations. Other aspects of combustor performance are equally, of not more important in turbine design. The temperature quality, or exit temperature profiles are important in designing durable turbine hardware. Historically, the temperature profiles have been reported in two ways. Profile Factor indicates the highest average temperature at a specific

spanwise location and the Pattern Factor indicates the maximum temperature at any location in the combustor exit plane. These values are expressed in equations 1 and 2.

$$\text{Profile Factor} = \frac{T_{\max,rad} - T_{ave}}{T_{ave} - T_{inlet}} \qquad (1)$$

$$\text{Pattern Factor} = \frac{T_{\max} - T_{ave}}{T_{ave} - T_{inlet}} \qquad (2)$$

Combustor concepts being pursued as part of the IHPTET program lend themselves to control of the exit temperature distribution. These concepts feature an array of fuel struts with multiple spanwise fuel injection points. This allows both spanwise and circumferential control of the fuel injection. Testing is planned to determine the effect of changes in the fuel injection profile on the exit temperature distribution. After this behavior is characterized, it is a simple matter to implement open loop control of the temperature profile.

While open loop control is relatively easy to achieve, closed loop control presents many more benefits. In theory, all that is required to implement closed loop control is a temperature sensor that can be mounted on the high pressure turbine vanes, and control logic to implement the system. The problem becomes the development of temperature sensors that can withstand combustor exit temperatures. Current temperature levels present a challenge for measurements in a laboratory rig environment and make direct measurement impossible in an engine environment.

The ability to actively control the temperature profiles in an engine allows for a higher performance and more durable engine. Manufacturing tolerances allow for combustor to combustor and fuel nozzle to fuel nozzle differences in temperature profiles. Temperature profiles can be influenced by small differences in combustor air distribution, fuel nozzle flow and compressor exit profile changes. Active control allows the engine to compensate for these differences and maintain the design temperature profile. In addition, as the engine degrades, the compressor exit profile changes and nozzle fuel flow may change. Active control allows the engine to compensate for these changes and prolong turbine life.

As fuel air ratios increase, simple temperature measurements may not be sufficient for useful control. Once a location in the combustor exit plane reaches stoichiometric, it has reached its maximum temperature. If this streak is richer than stoichiometric, the temperature may actually be lower. The average temperature rise across the combustor can continue to rise however. As shown by equation 2, this can artificially drive the pattern factor number down and conceal potential problems in the turbine. To address this problem, a new parameter is coming into favor by combustor and turbine designers. The Fuel/Air Factor (FAF) is defined as:

$$\text{FAF} = \frac{\text{FAR}_{\max} - \text{FAR}_{\text{ave}}}{\text{FAR}_{\text{ave}}} \qquad (3)$$

This parameter is able to accommodate local fuel air ratios above stoichiometric without flattening out as pattern factor does, as shown in Figure 3.

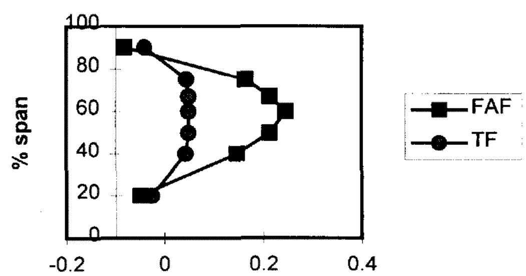

Figure 3

This phenomenon will also be present in the engine at very high fuel air ratios. Control of these rich streaks will require the development of instrumentation, which can

not only withstand the high temperature, but is capable of sensing products of combustion that may continue to react downstream.

ACOUSTIC CONTROL

Control of acoustic instabilities in gas turbine engines is a much more complex problem than the control of temperature profiles. Combustor rumble or augmentor screech can have a severe impact on the life of components. Acoustic instabilities can not only reduce the efficiency of the engine, but can cause serious damage to hardware, often causing component failures. Current passive control techniques include changing fueling schemes in areas of the envelope prone to instability, and hardware changes to the screech control section of the augmentor liner or combustion liner.

Active control of instabilities includes sensing both that the instability exists, as well as the frequency of the instability. Once the frequency is known, the fuel supply, or air supply can be pulsed in such a manner as to eliminate the instability. In a simpler form of control, the fuel distribution can be modified only when instability is present as opposed to any time the aircraft is operating at a certain point in the envelope, or performing a specified throttle maneuver. This latter method requires fuel injection patterns to be determined empirically for all conditions in order to determine solutions.

TECHNOLOGY NEEDS

Several key technologies are required in order to make active combustion control a reality. The most pressing need is for temperature sensors capable of withstanding temperatures seen at the combustor outlet that do not interfere with engine operation, and are flight quality. The sensors must be able to withstand high temperatures for 2000 hours of engine operation. In addition, they must be able to withstand the operational environment that Navy aircraft are subjected to.

In order to actively control combustion instabilities, sensors must be developed that can detect the presence of and determine the frequency of the instability. The control system must be able to differentiate between combustion instability and other vibrations that are common to military aircraft. Once instability is detected, actuators that are capable of pulsing the fuel at between 0 and 1 kHz and lasting 5.4 billion cycles are required. Again, these actuators need to be flight weight, and small enough to fit several in a single fuel nozzle.

MEASUREMENT & ACTUATION

State-of-the-art sensor technology allows only rudimentary insight into the real-time dynamics of combustion. The hurdle becomes living and working in 3500°+ Fahrenheit for long duration and providing useful information. What do we need to know, and what are we trying to control? The overarching goals of the Navy's controls and diagnostics S&T program focus on performance, safety and life cycle cost (LCC).

Any active control system derives value from its ability to accurately sense the current state of the plant and control the system dynamics within a minimal tolerance band. Understanding gas path parameters in the hot section is a tough problem to overcome. The solution lies in one of three options.

First, develop in-situ sensors capable of providing combustor gas path temperature, pressure, acoustic, emissions, or other critical parameters. These sensors or sensor sets must provide profile information in a non-intrusive manor. One value of active combustion control is to add life to the turbine. Placing rakes of sensors upstream of the turbine inlet is in direct violation of the concept. The technology hurdle becomes developing non-intrusive methods of measuring temperature and pressure profiles. Additionally, concepts to measure the acoustic state of the system need to be developed. This area overlaps with concepts

already mentioned concerning overall system health monitoring. Vibrations are closely monitored on existing engines in hopes that incipient failures can be identified. Improving on the fidelity of these measurements can help to provide combustion acoustic information. Concepts such as laser interferometry, and MEMS accelerometers should be explored.

The second option for providing combustor feedback poses a pure analytical solution. Adding sensors to an engine is generally not desirable. Therefore, if a real-time combustor model could be developed all gas path information would be known. However, real-time models of combustion systems are hard to come by, and provide a qualification nightmare. Many questions concerning model validation both initially and throughout the life of the engine would need to be address prior to fleet introduction. The Navy isn't ready to run a sensorless control system.

The third option is to develop a hybrid system relying on accurate real-time combustion system models to provide the "impossible" to measure parameters with advanced sensors providing tuning and feedback for the model. This type of system allows for much more than just a combustion controller. It provides valuable diagnostic information. As the model is "tuned" to match the existing state of the engine, these tuning parameters allow maintainers to track and predict the system health. In reality, this combustion model would simple be a portion of a greater engine system real-time model capable of optimizing the system performance based on any number of metrics such as; thrust, specific fuel consumption, component life, etc...

IMPLEMENTATION

Conceptually, we have designed the system and identified its correlation to existing initiatives within the Navy & DOD. From this baseline, the challenge focuses on developing components that will operate in a real-world environment. It's assumed that the control scheme will rely on modern multi-input multi-output algorithms optimizing a cost function with a variety of actuation points at hand. The actuation suite is fairly limited given the simplicity of a gas-turbine combustion system. Prime movers for affecting the combustion system dynamics will be the fuel delivery system. Pattern factor and acoustic characteristics will be affected by spatially and temporally actuating fuel delivery requiring that each fuel nozzle be controllable. As yet other methods have not been identified. Methods like direct flow modification via vortex generators, bleed or blowing devices are concepts that from a practical standpoint provide a reliability & safety liability. However, flow modification devices might address some of the overarching goals of active control, in which case the technology effort needs to focus not only on the physics but reliability & life issues as well.

SOFTWARE/ELECTRONIC HARDWARE

As with many intelligent engine concepts implementation requires a foundation capable of handling the necessary computing horsepower to run the real-time algorithms and engine system models. Most digital control systems contain components such as a 1553 data bus which can be used. However, few systems contain the necessary "extra" CPU & memory to run the model plus active control algorithms plus control schedules. Therefore, active model based combustion control will depend on the ability to attach or design in the necessary processing power. Future systems will have this as a built-in feature, legacy systems will require some degree of flexibility to accommodate additional control boxes.

ACC IN THE NAVY

The Intelligent Engine Initiative (AF/Navy) is focused at using advanced sensing, actuation, and information technology to maximize performance while minimizing operation and support cost. Areas focused on are: Nonlinear adaptive control;

Prognostics/diagnostics life-influencing factors; Active control for performance and durability; Advances in sensing and actuation. Within these areas are Navy "unique" requirements and technology development areas. Specifically, in the turboshaft area, requirements for a technology leap applied to missions such as search and rescue (SAR), sub hunter, and vertical replenishment (VERTREP) need to be addressed. The unique need for reliability and performance durability (i.e. prognostic and diagnostic improvements) while living in a severe corrosive environment drive technology planning to include detection/prevention algorithms for corrosion driven performance loss and system failures. Adaptive control to overcome this performance loss coupled with novel diagnostic algorithms providing on-wing system health and component level life management enable SAR, sub hunter, and VERTREP mission cost reduction as well as readiness improvement. Most engines operating in these missions are removed for performance loss rather than life issues. By improving health monitoring and integrating this with adaptive control we can improve engine durability, reliability, and reduce life cycle cost. Completing the Intelligent Navy Engine with active cold and hot section control allows real-time management of performance, engine and accessories health, and system efficiency while maintaining optimum life. Many of the turboprop/turboshaft needs for control technology overlap those required by turbofan/turbojet.

This Navy technology roadmap relies on advances in many areas of active control, primarily active compressor & combustion control. ACC seems to offer a solution that addresses many Navy requirements at once and should be a priority for technology development.

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PAPER -4, M. Richman

Question (F. E. C. Culick, USA)

You mentioned the possibility of new configurations for combustors, e.g., spray bars. Hasn't that sort of suggestion encountered resistance from the people designing combustors in industry?

Reply

The contractors (engine manufacturers) have been very willing to look at revolutionary designs. More resistance has come from the Department of Defense (DoD).

Question (D. A. Santavicca, USA)

What temperature resolution/accuracy are you looking for in your turbine inlet temperature sensor?

Reply

An accuracy of ±50° F at stoichiometric temperatures is required.

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